An Arc of Young Stars in the Halo of M82[1]

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ABSTRACT

The properties of the brightest resolved stars in an arc that was originally identified by Sun et al. (2005) and is located in the extraplanar regions of M82 are discussed. The stars form an elongated structure that is traced over a projected area of 3.0×0.8 kpc. The integrated brightness is $M_V \sim -11$, while the total stellar mass is between 3×10^5 $M_\odot$ and 2×10^6 $M_\odot$. If there is only foreground extinction then the youngest stars have a metallicity $Z \geq 0.008$ and an age $\log(t_{yr}) \sim 7.75$; thus, the youngest stars formed at roughly the same time as stars in tidal features that are associated with other M81 Group galaxies. If the arc is dispersing then it will deposit young, chemically enriched stars into the M82 halo.

Subject headings: galaxies: individual (M82) – galaxies: evolution – galaxies: starburst – galaxies: halo

1. INTRODUCTION

As one of the closest galaxy groups, the M81 Group is an important laboratory for probing galaxy evolution. Unlike the Local Group, the M81 Group contains galaxies that have experienced cosmologically recent interactions, with the elevated levels of star formation in M82 and NGC 3077 likely triggered by an encounter with M81 within the past few hundred million years (Brouillet et al. 1991; Yun, Ho, & Lo 1994). Subsequent studies of the stellar

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fossil record in M82 have since found evidence of wide-spread elevated levels of star-forming activity roughly 0.5 - 1 Gyr in the past (e.g. de Grijs, O'Connell, & Gallagher 2001; Mayya et al. 2006). More recent epsiodes of star-forming activity have been restricted to the inner regions of M82 (e.g. Gallagher & Smith 1999; Forster Schreiber et al. 2003; Smith et al. 2006).

The interactions in the M81 Group have had a major impact on the intracluster environment. Feedback from supernovae power an outflow from M82 that injects chemically enriched material into the intracluster medium (e.g. Shopbell & Bland-Hawthorn 1998), which in turn may interact with surrounding clouds (e.g. Devine & Bally 1999). Tidal interactions can also pull material from galaxies, and morphogical signatures of this activity are seen near some M81 Group galaxies (e.g. Karachentseva, Karachentsev, & Boerngen 1985). The molecular material in M82 has been severely disrupted (Walter, Weiss, & Scoville 2002), and the morphology of the galaxy has been affected; while it now has an amorphous appearance, there are indications that it may have been a late-type spiral or irregular galaxy before the encounter with M81 (e.g. O'Connell & Mangano 1978).

Sun et al. (2005) find an arc-like feature in the southern regions of M82, which they refer to as 'M82 South'. This object has a flat spectral energy distribution (SED) at visible wavelengths, a relatively high surface brightness, and is also seen in the UV (Figure 2 of Hoopes et al. 2005). M82 South is located just outside of the region imaged for the M82 Surveys Mosaic with the HST ACS (Mutchler et al. 2007). It can be anticipated that at least some of the light from M82 South originates from young stars, and resolving stars in such a feature would be of great interest. The light that has been detected from other sources in the extraplanar regions of M82 appears to be from excited gas, and not stars. The detection of stars in M82 South would thus make it the first stellar structure to be detected in the outer regions of M82. Moreover, studies of the spatial distribution of stars in M82 South will also provide information for probing its structural properties and origins. Finally, if M82 South contains young stars and is not a gravitationally bound structure then it may contribute to the stellar content of the M82 halo. During the past decade it has been demonstrated that the outer regions of nearby spiral galaxies contain stars spanning a range of ages and metallicities (e.g. Brown et al. 2006; Mouchine 2006), and the disruption of structures like M82 South will diversify the stellar content of the halos of interacting galaxies. In this letter, we report on the detection of young stars in M82 South. It is shown that the youngest stars in M82 South have ages that are comparable to those of stars in tidal features near other M81 Group galaxies.

2. OBSERVATIONS

The data were obtained with the MegaCam imager (Boulade et al. 2003) on the 3.6 metre Canada-France-Hawaii Telescope (CFHT) as part of a wide-field survey of M81 and M82. The detector in MegaCam is a mosaic of 36 2048×4612 pixel^2 CCDs, and each exposure covers roughly 1 degree^2 with 0.185 arcsec pixel^{-1}. Four 360 second exposures were recorded through r' and i' filters with the midpoint between M82 and M81 centered on the detector mosaic. Stars in the final images have 0.8 arcsec FWHM in r' and 0.7 arcsec FWHM in i'.

The raw data were processed with the ELIXER package at the CFHT, and this included bias subtraction, flat-fielding, and fringe removal. The reduced images were then aligned and combined by the author at the HIA. The photometric measurements were made with ALLSTAR (Stetson & Harris 1988), using a point-spread function (PSF) constructed with the DAOPHOT (Stetson 1987) PSF routine. The photometric calibration is based on the zeropoints that are placed in MegaCam data headers as part of the ELIXER processing. These zeropoints are calculated from standard star observations that are recorded as part of the MegaCam queue observing process.

3. RESULTS

3.1. The Morphology and Integrated Brightness of M82 South

M82 South was discovered independently by the author when the locations of stars that were photometered with DAOPHOT were plotted (Davidge 2008 in preparation). A section of the final i' MegaCam image that includes M82 South is shown in Figure 1. An expanded view of the region near M82 South is shown in the lower right hand corner of Figure 1, while the spatial distribution of sources in this same area with i' between 22.5 and 24.5, which is the magnitude range where stars associated with M82 South are seen (§3.2), is shown in the lower left hand corner. M82 South is 5.4 arcmin from the center of M82 (~ 6 kpc projected distance if $\mu_0 = 27.9$ – Sakai & Madore 1999), and its stars form a band with a width of ~ 40 arcsec (~ 0.8 kpc). A prominent strip of diffuse light falls near the southern edge of the stellar distribution. The stellar density in the richest part of M82 South is ~ 120 arcmin^{-2}, whereas in the areas marked 'Background' in Figure 1 the mean stellar density is at least $\sim 6\times$ lower. The Western end of M82 South is marked by a distinct drop in stellar density, while there may be a tendency for the stars in M82 South to broaden or curve north at the eastern edge of Figure 1.

The integrated brightness within ±20 arcsec of the M82 South ridgeline is $r' \sim 16.6 \pm 0.5$, so that $M_V \sim -11 \pm 0.5$, and the mean surface brightness is ~ 26 mag arcsec^{-2}. To make this measurement, the background was measured on both sides of M82 South, in the regions marked in Figure 1, and the results were averaged to obtain a background level that is appropriate for the ridgeline of M82 South. If M82 South is a simple stellar system with an age log(t) ~ 7.75 (see below), then $\log(M/L_V) \sim -0.85$, (e.g. Mouchine & Lancon 2003), where M/L_V is the mass-to-light ratio in V; the total mass is then $(3 \pm 2) \times 10^5$ $M_\odot$. This is a lower limit, since M/L_V will be higher if an older population is present. To estimate an upper mass limit $M/L_V = 1$ was assumed, and the total mass in this case is $(2 \pm 1) \times 10^6$ $M_\odot$.

3.2. Stars in M82 South

The $(i', r' - i')$ CMDs of objects within ±20 arcsec of the M82 South ridgeline are shown in the middle row of Figure 2. The CMDs of the background/control fields indicated in Figure 1 are also shown. The control fields to the north east and south west of M82 South contain very different numbers of stars, due to the gradient in stellar density in the outer regions of M82, and this gradient makes it difficult to place the northern boundary of M82 South with confidence. With the caveat that the northern control field may contain some stars belonging to M82 South, then it appears that no more than one third of the sources within ±20 arcsec of the M82 South ridgeline do not belong to M82 South.

Contamination from foreground Galactic stars, background galaxies, and stars in the M82 field can be accounted for statistically by assessing the color and brightness distributions of objects in M82 South. The net $r'-i'$ color function of sources with i' between 23.5 and 24.5 ($M_{i'}$ roughly between –4.5 and –3.5), constructed by subtracting the mean color function of the control fields from that in M82 South, and the net i' luminosity function (LF) of objects in M82 South, constructed by subtracting the mean LF of sources in the control fields from that in M82 South, are shown in Figure 2. The color distribution of objects in M82 South runs from $r' - i' \geq -0.3$ to 0.5, while the LF indicates that the brightest stars in M82 South have $i' \sim 23$.

The $(M_{i'}, (r'-i')_0)$ CMD of stars within ±20 arcsec of the M82 South ridgeline is shown in Figure 3. A distance modulus of 27.95 (Sakai & Madore 1999) has been adopted, with a foreground reddening $A_B = 0.10$ (Burstein & Heiles 1984). There is dust in the M82 outflow (e.g. Heckman, Armus, & Miley 1990), and so the foreground reddening is a lower limit to the actual reddening. This being said, M82 South is much further from the disk plane than the area where dust has been detected. Furthermore, the mean colors and color distributions

of stars in the eastern and western portions of M82 South are not different, indicating that if dust is present then it is very uniformly distributed.

Also shown in Figure 3 are evolutionary tracks from Girardi et al. (2004) with Z = 0.008 and Z = 0.019 for ages $\log(t_{yr}) = 7.5$ and 8.0. While not shown in Figure 3, isochrones with Z = 0.0001 place the red supergiant locus at $r' - i'$ colors that are $\sim 0.2 - 0.3$ smaller than those with Z = 0.008. With the caveat that up to one third of the stars probably do not belong to M82 South, then the red envelope of stars in Figure 3 argues for $Z \geq 0.008$, which is consistent with the metallicity of young stars in the disk of M82 (e.g. Mayya et al. 2006). The stars in M82 South thus formed from chemically enriched gas.

The ages of the youngest stars can also be estimated from the comparisons in Figure 3. The large number of stars with $M_{i'}$ between –4 and –5 and $r' - i'$ between –0.1 and 0.3 is consistent with $\log(t_{yr}) = 7.5 – 8.0$; thus, $\log(t_{yr}) = 7.75$ is adopted for the youngest stars. An interesting check of this age comes from a comparison with Ho IX, which has an SED at visible wavelengths that is very similar to that of M82 South (Sun et al. 2005). Makarova et al. (2002) find that the majority of stars in Ho IX have ages $\log(t_{yr}) = 7.8$, in excellent agreement with what is found in M82 South.

4. DISCUSSION

Deep images obtained with the CFHT MegaCam have been used to resolve individual stars in M82 South. The youngest stars have ages $\log(t_{yr}) = 7.75$ and $Z \geq 0.008$. Thus, despite having a projected distance of ~ 6 kpc off of the M82 disk plane, M82 South recently formed stars from chemically enriched material.

Lacking kinematic information, the physical separation between M82 South and the main body of M82 is a matter of speculation. M82 South is not in the disk plane of M82, and it seems likely that M82 South is associated with the extraplanar regions of M82, as opposed to being an outlying structure on the far or near side of the M81 group, given its close projected proximity to M82. The general morphology of M82 South in Figure 4 of Sun et al. (2005) is reminiscent of the filamentary features that originate from M81, albeit on a much smaller scale. Thus, M82 South physically resembles features seen in the outer regions of other galaxies.

Adopting the mass estimates in §3 then it is unlikely that M82 South will be a long-lived feature. If the mass of M82 is 10^{10} $M_\odot$ (Sofue et al. 1992), then the tidal radius of M82 South is a few tenths of a kpc if the projected separation of 6 kpc corresponds to the actual separation. To escape tidal pruning, M82 South would have to be 50 – 100 kpc away from

M82, on the side of M82 that is furthest from M81. If it is within 10 – 20 kpc of M82 then M82 South will survive for only a few orbital crossing times about M82, or $\sim 10^8 - 10^9$ years, depending on the actual distance from M82 and the nature of the orbit about the larger galaxy.

Could M82 South be the remnant of a pre-existing dwarf galaxy that was disrupted by M82? This is unlikely, as the metallicity of stars in M82 South suggest that such a satellite would have had an LMC-like mass, which is roughly 25 – 50% that of M82. The disruption of such a massive galaxy would leave significant tidal debris trails, which are not seen.

There are conspicuous signatures of galaxy-galaxy interactions throughout the central regions of the M81 Group. Gas bridges link galaxies (e.g. Yun et al. 1994; Boyce et al. 2001), and there are objects that may be tidal dwarfs (Karachentsev et al. 2002; Makarova et al. 2002). Could M82 South be such a tidal fragment? The youngest stars in M82 South have ages near 50 Myr, and there was contemporaneous star formation in other candidate tidal features, such as Ho IX, the Garland, and the Arp-Loop (e.g. Makarova et al. 2002; Sakai & Madore 2001). However, tidal dwarfs are predicted to be gas-rich (e.g. Barnes & Hernquist 1992), and the HI map of Yun et al. (1994) does not show an HI concentration near M82 South, which is in marked contrast to Ho IX and the Arp-Loop. This being said, the presence of diffuse Hα emission (Figure 2 of Hoopes et al. 2005) suggests that M82 South may not be completely devoid of gas.

The outflow from M82 has ejected at least 3×10^8 M$_\odot$ of gas out of the disk plane (Walter et al. 2002), and M82 South may have condensed out of some of this material. The 'Cap' (Devine & Bally 1999) is located some 11 kpc to the north of the M82 disk plane, and is thought to have formed in a shock that occured when the outflow encountered clouds surrounding M82 (e.g. Lehnert et al. 1999; Strickland et al. 2004). The material in the Cap is metal-enriched (e.g. Hoopes et al. 2005; Strickland & Heckman 2007; Tsuru et al. 2007), and there are knots that may indicate the onset of star formation, although stars have yet to be resolved. If M82 South is a related structure then it must be in a later stage of evolution. M82 South is a much weaker source of x-ray (e.g. Tsuru et al. 2007) and Hα (Hoopes et al. 2005) emission than the Cap, but is a source of much stronger UV emission, which is concentrated in at least three knots (Hoopes et al. 2005). While the absence of detectable x-ray emission indicates that the material in M82 South is not at present experiencing shock excitation, such activity in the past might have triggered star formation. The drop in stellar density that defines the western edge of M82 South might then mark the spatial extent of star-forming material.

If M82 South is a genuinely young object then it will not have an underlying population of old stars. Deep high angular resolution imaging will provide constraints on objects such as

stars evolving on the red giant branch; if such stars are present then they would indicate an age of at least ~ 1 Gyr for M82 South. The detection of such stars would suggest that M82 South is probably more distant from M82 than 6 kpc, given the disruption time estimated above.

We conclude by noting that if structures like M82 South are common in interacting galaxies then they may have a significant impact on the extraplanar stellar content of these objects. If M82 South is dispersing then its young metal-rich stars may eventually migrate into the extraplanar regions of M82 or the intragalactic medium in the M81 group. If similar structures have formed previously and dispersed near M82 then deep imaging of the outer regions of M82 should reveal stars with a wide range of ages and metallicities. The CMDs of the north east control field in Figure 2 and in the extraplanar regions of other galaxies (e.g. Mouchine 2006) suggest that such a dispersion in stellar content is present.

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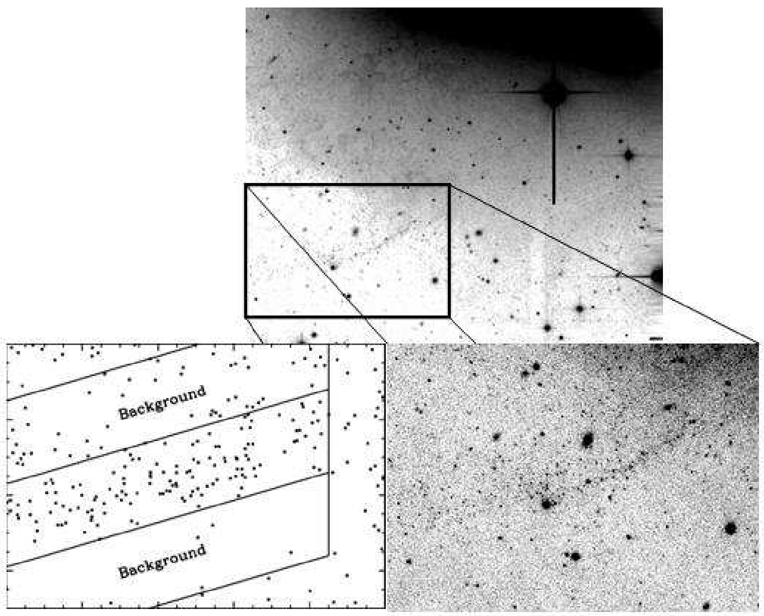

Fig. 1.— The top portion of this figure shows a 370 × 370 arcsec^2 section of the final processed i' MegaCam image, with north at the top and east to the left. The gradient in surface brightness due to stars in M82 is clearly seen. The 180 × 150 arcsec^2 area around M82 South is shown in the lower right hand corner, while the spatial distribution of stars with i' between 22.5 and 24.5 in this same area is shown in the left hand inset. The regions used in the analysis that sample the main concentration of stars in M82 South and the background/control fields are indicated.

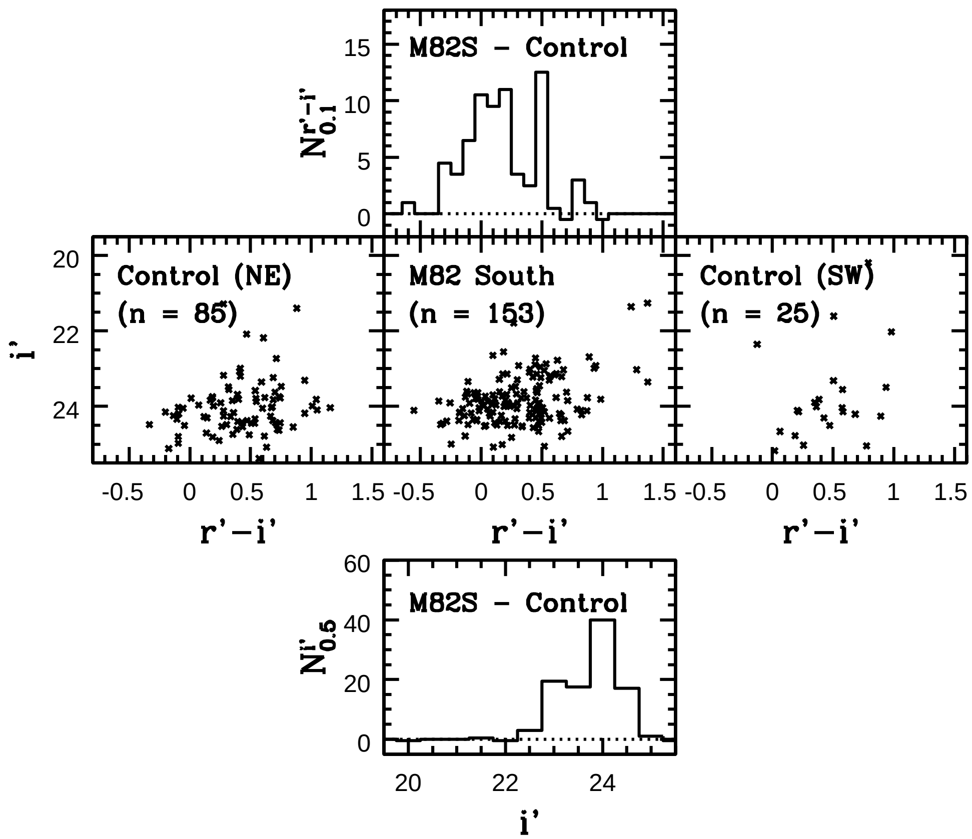

Fig. 2.— The $(i', r' - i')$ CMD of objects in a ±20 arcsec region centered on the ridgeline of M82 South and in control fields located ±40 arcsec on either side of M82 South are shown in the middle row. The number of objects in each CMD is listed, and there is a clear excess of sources associated with M82 South. The result of subtracting the mean $r' - i'$ color distribution of objects with i' between 23.5 and 24.5 ($M_{i'} \sim -4.5$ to –3.5) in the control fields from the color distribution of sources in M82 South is shown in the top row, where $N_{0.1}^{r'-i'}$ is the net number of stars in this brightness interval per 0.1 magnitude $r' - i'$ interval. Note that the color distribution runs from $r' - i' = --0.3$ to 0.5, with a peak near $r' - i' \sim 0$. The LF that results from subtracting the mean LF of the control fields from the LF of M82 South is shown in the bottom panel, where $N_{0.5}^{i'}$ is the net number of stars per 0.5 magnitude i' interval. Note that the majority of stars in M82 South have $i' \geq 23.0$, which corresponds roughly to $M_{i'} \geq -6$.

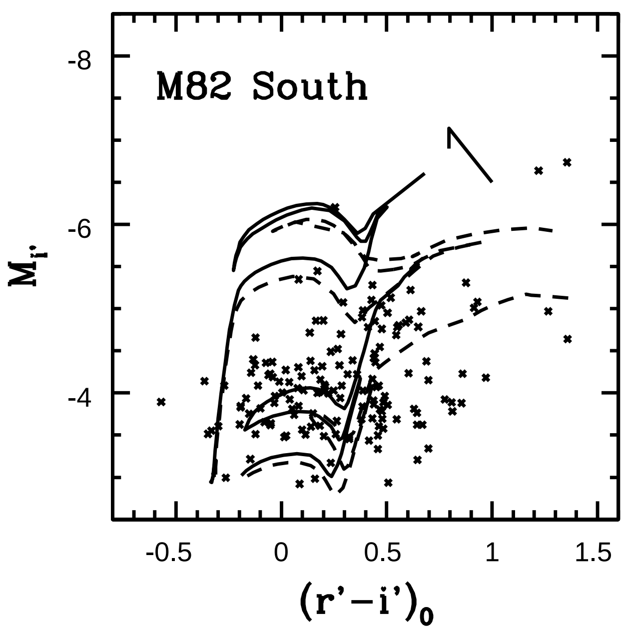

Fig. 3.— The $(M_{i'}, (r' - i')_0)$ CMD of the ±20 arcsec region centered on M82 South. A reddening vector with a length that is appropriate for $A_V = 1$ is shown. The solid lines are Z = 0.008 isochrones with ages $\log(t_{yr}) = 7.5$ and 8.0 from Girardi et al. (2004), while the dashed lines are isochrones with the same ages, but Z = 0.019. Note that the brightnesses of stars with $(r' - i')_0$ between –0.3 and 0.5 favours an age between $\log(t_{yr}) = 7.5$ and 8.0, while the red envelope of stars suggests that $Z \geq 0.008$.